

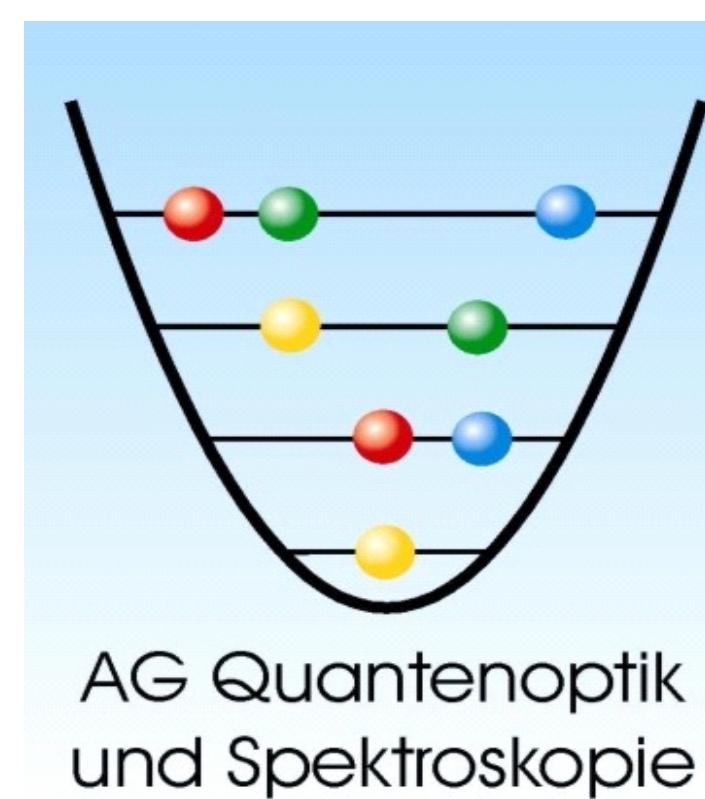


Investigating a new qubit candidate: $^{43}\text{Ca}^+$

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Introduction

We have assembled a new ion trap apparatus including a novel laser system capable of trapping strings of $^{43}\text{Ca}^+$ ions. The qubit will be encoded in the hyperfine levels of the ground state ($F=4, m_F=0$ and $F=3, m_F=0$) and driven by Raman transitions. This type of qubit encoding is insensitive to phase decoherence due to laser frequency and magnetic-field noise. Furthermore, a Raman scheme will allow greater gate fidelities due to the increased control over motional couplings (large Lamb-Dicke factor, suppression of transverse mode excitation).

Advantages of ions with half odd-integer nuclear spin

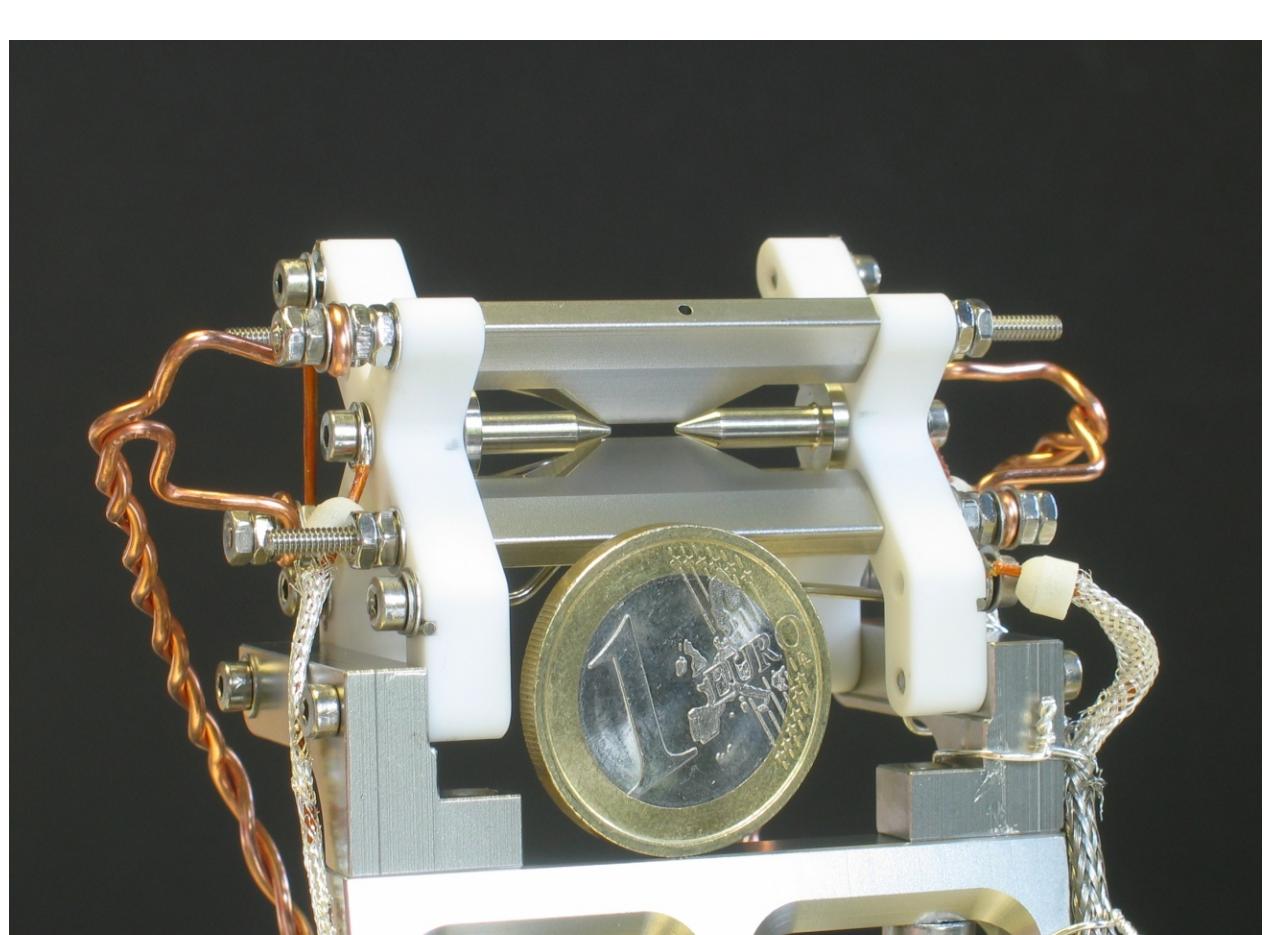
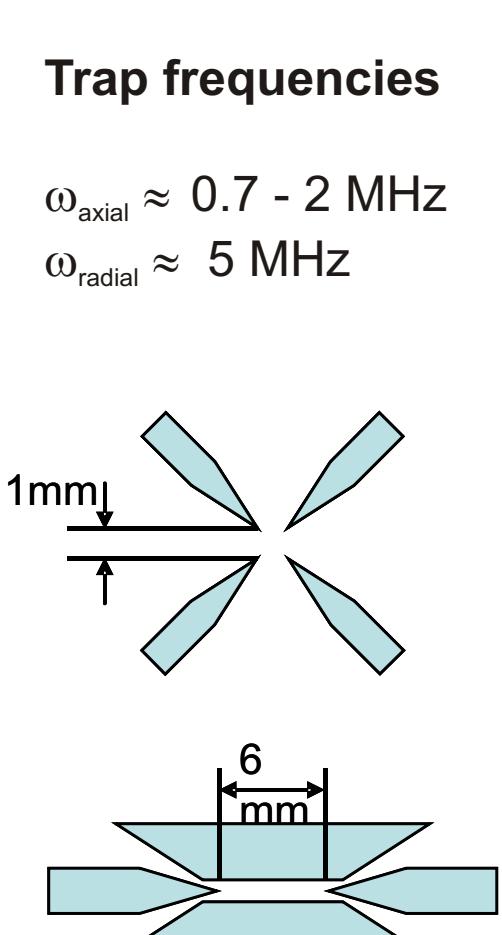
- no 1st order Zeeman shifts for $m_F=0$ qubit levels
- no spontaneous decay of qubit levels
- Raman transitions much less demanding on laser stability
- large Lamb-Dicke Faktor (\rightarrow faster gates)
- better addressability
- choice of beam geometry allows for
 - excitation of longitudinal oscillator modes without driving transverse modes
 - exclusive excitation of carrier transitions

Comparison of some ion species

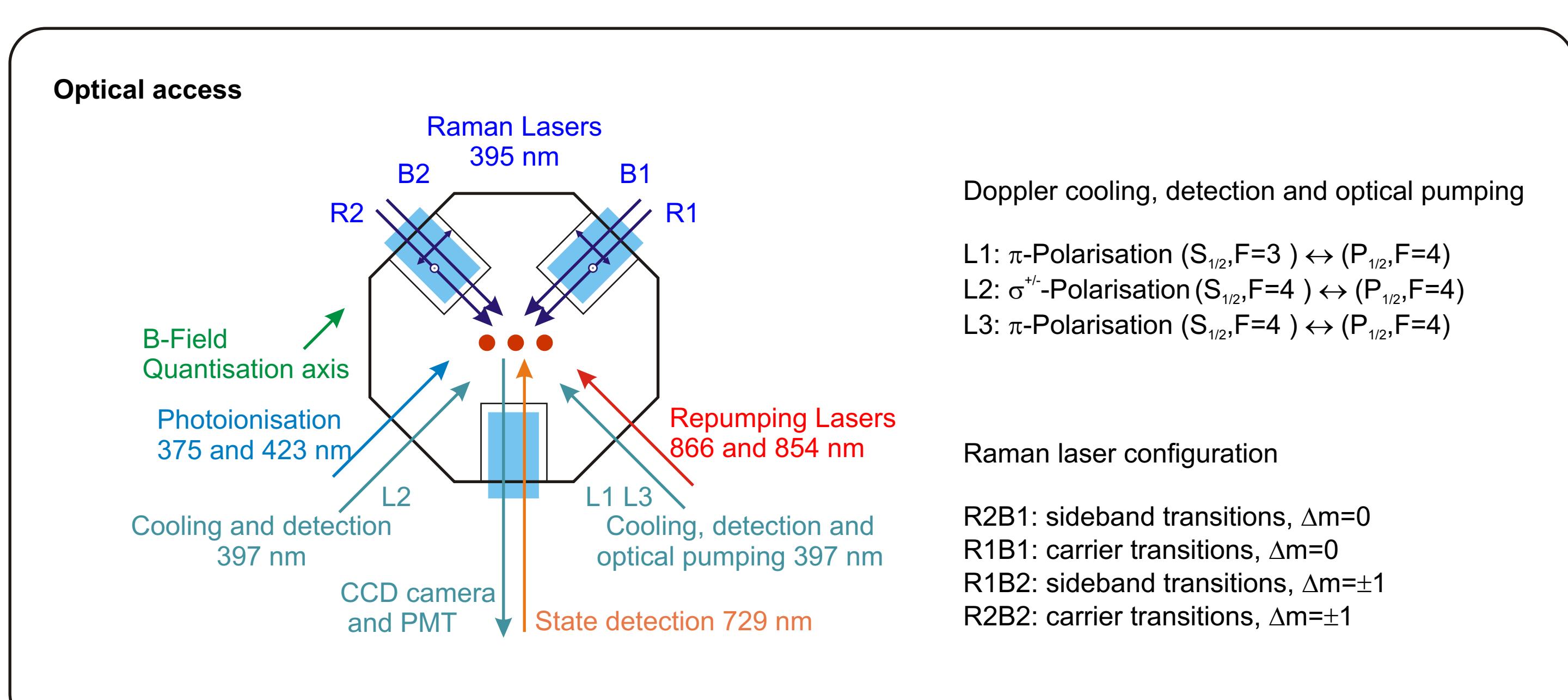
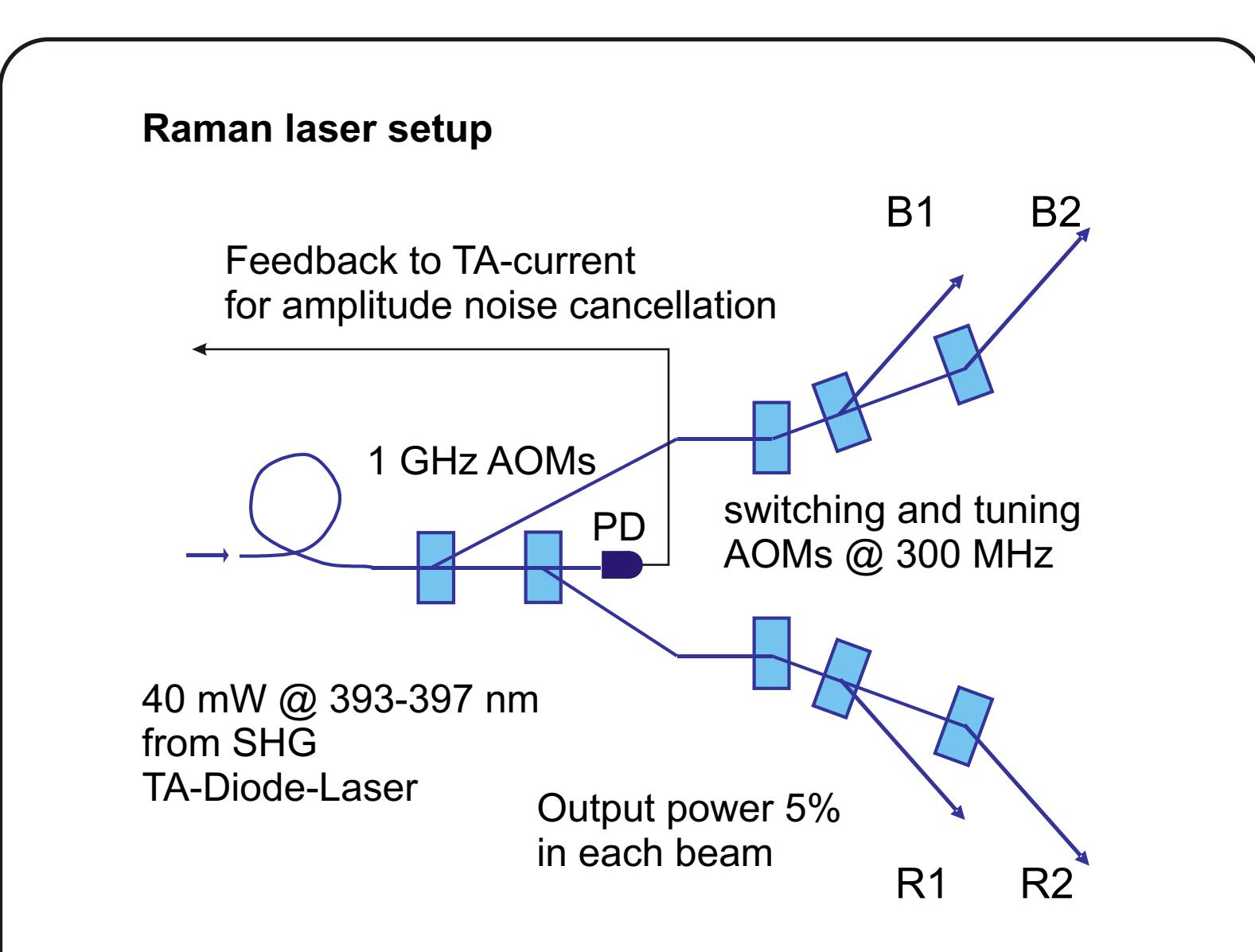
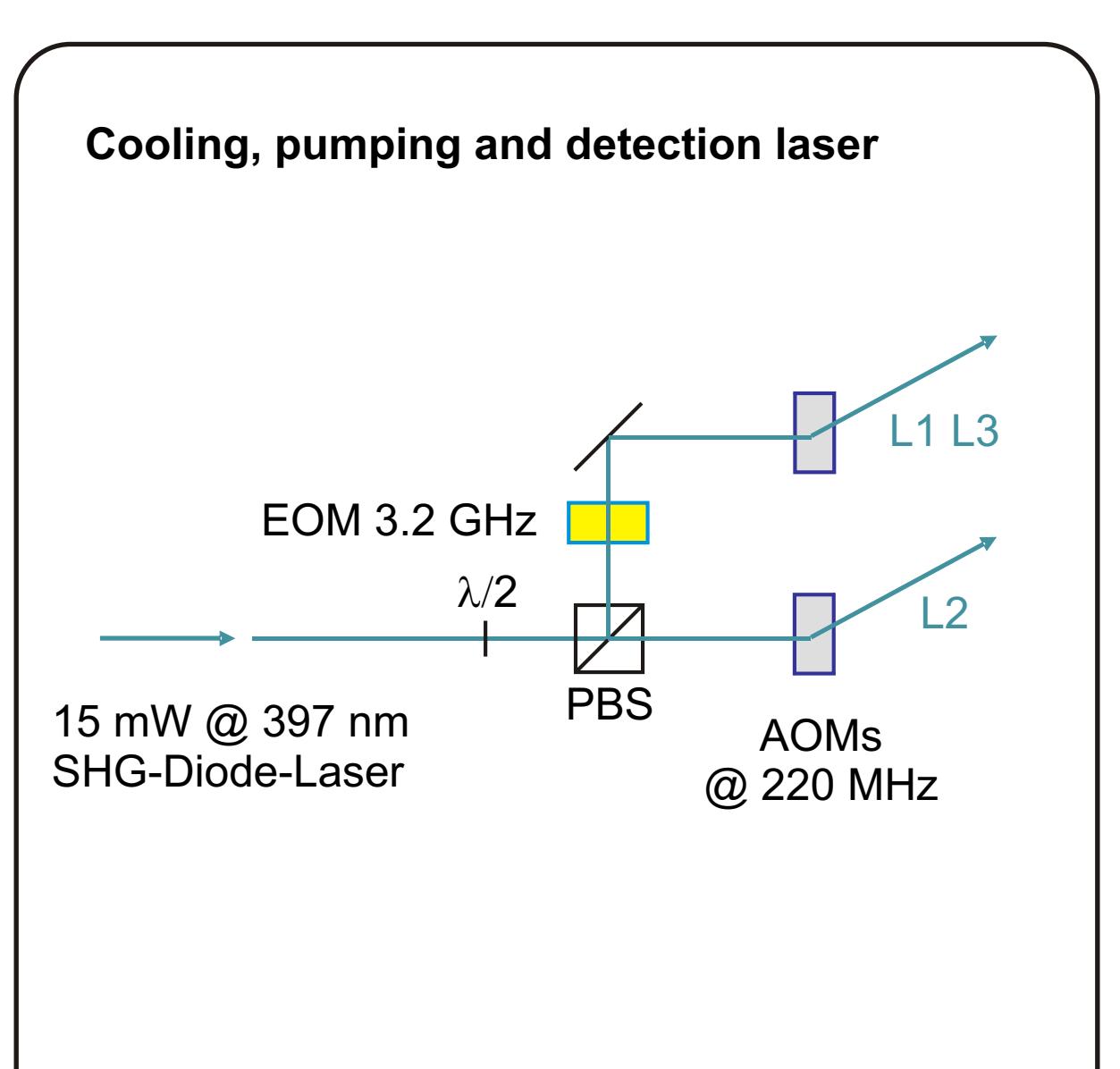
| ion | I | Δ_{HFS} (GHz) | $P_{\text{spont.lem.}}$ | photoion. | $S_{1/2} \leftrightarrow P_{1/2}$ (nm) |
|--------------------------------|-----|-----------------------------|-------------------------|-----------|----------------------------------------|
| ⁹ Be ⁺ | 3/2 | 1.25 | 8.7×10^{-4} | no | 313 |
| ²⁵ Mg ⁺ | 5/2 | 1.8 | 1.4×10^{-4} | yes | 280 |
| ⁴³ Ca ⁺ | 7/2 | 3.3 | 3.0×10^{-5} | yes | 397 |
| ⁸⁷ Sr ⁺ | 9/2 | 5.0 | 8.0×10^{-6} | no | 422 |
| ¹¹³ Cd ⁺ | 1/2 | 15.2 | 5.3×10^{-6} | no | 229 |
| ¹⁹⁹ Hg ⁺ | 1/2 | 40.5 | 1.8×10^{-6} | no | 194 |

P: Probability of spontaneous em. during one Raman Rabi oscillation
from Phil. Trans. R. Soc. A 361(1808), 2003

Trap

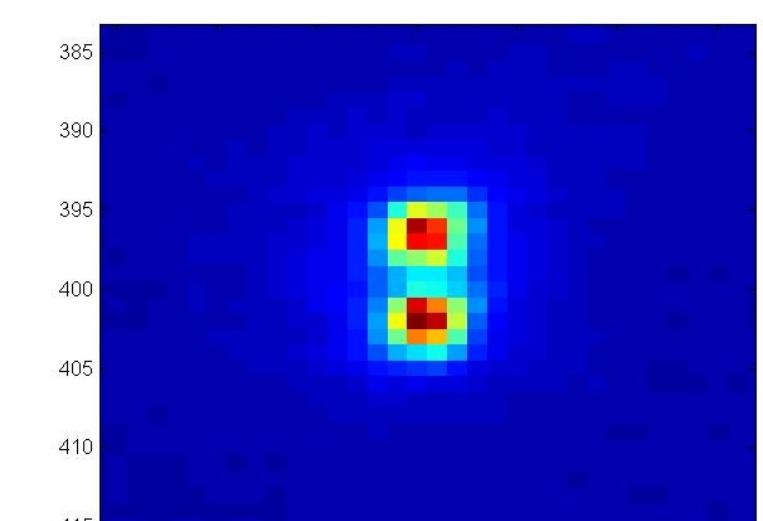


Lasers and optical access



Status of the experiment and next steps

- Cooling/pumping/detection laser and the repumping lasers are installed
- A Raman laser system providing light at 393-397 nm with 3.2 GHz splitting is installed
- The laser for the quadrupole transition has been locked to a high finesse cavity
- Experimental control has been established including frequency generation for 729 nm and the Raman-Laser AOMs
- We have loaded $^{40}\text{Ca}^+$ and $^{43}\text{Ca}^+$ using photoionisation
- We observed single ions and strings of $^{43}\text{Ca}^+$
 \rightarrow Doppler cooling works



Next steps:

- transfer of $|F=4\rangle$ population to $D_{5/2}$ with the 729 nm laser
- state detection with photo-multiplier and CCD camera
- optical pumping to the $|F=4, m_F=0\rangle$ state in the Lamb-Dicke limit
- observation of Rabi flops between $|F=4, m_F=0\rangle \leftrightarrow |F=3, m_F=0\rangle$
- Raman-sideband cooling to the motional ground state on the $|F=3, m_F=3\rangle \leftrightarrow |F=4, m_F=4\rangle$ transition
- transfer to $|F=4, m_F=0\rangle$ using adiabatic passage with the 729 nm laser
- coherent manipulation on the qubit transition

Cirac-Zoller CNOT gate

We plan to implement a Cirac-Zoller CNOT gate with a high fidelity. While keeping the advantages of single ion addressability (flexible programming and state tomography), with $^{43}\text{Ca}^+$ we can overcome the current limitations of $^{40}\text{Ca}^+$ (laser frequency noise, sensitivity to magnetic-field fluctuations and off-resonant excitations).

From a full master-equation simulation of the quantum gate, we estimate the error budget for a Cirac-Zoller gate with $^{43}\text{Ca}^+$ as follows:

| Error source | Magnitude | Contribution to fidelity loss |
|--------------------------------------------|--------------------------------------------|-------------------------------|
| Laser phase noise and magnetic field noise | ~ 3 Hz (FWHM) | $\sim 0.6\%$ |
| Laser intensity fluctuations | $\sim 3\%$ peak to peak | $\sim 0.1\%$ |
| Light shifts | for $t_{\text{gate}} = 1$ ms | $\sim 0.2\%$ |
| Addressing error | 2% in Rabi frequency (at neighbouring ion) | $\sim 0.5\%$ |
| Off-resonant excitations | for $t_{\text{gate}} = 1$ ms | $\sim 0.1\%$ |
| Total fidelity loss | $\sim 1.5\%$ | |
| Expected gate fidelity | $\sim 98.5\%$ | |

Cooling and state preparation

